

RECENT ADVANCES IN THREE-DIMENSIONAL PRESSURE RELIEVING CUSHIONS FOR THE PREVENTION OF PRESSURE ULCERS

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ABSTRACT

Polyurethane (PU) foam is one of the most common materials used in the development of pressure relieving cushions. However, it suffers from reduced efficiency in terms of thermophysiological comfort, cost, recycling and importantly, creating a suitable environment for the prevention of pressure ulcers. The paper presents research carried out at the University of Bolton, in the development of pressure relieving cushion applications using three-dimensional (3D) warp knitted spacer fabrics. Three properties, pressure distribution, air permeability, and heat resistance of 3D warp knitted spacer fabrics are focused on, with particular emphasis on pressure distribution in the development of improved performance and efficacy of cushion applications. This research includes the development of a novel technique for measuring pressure distribution while under simulated loading conditions.

Using this system, fully patented novel and smart 3D knitted spacer Airospring® cushions were developed, with the following features:

- 1. The introduction of a shaped/contoured surface interface was able to re-distribute high pressure points normally located in vulnerable areas of an immobile and seated person.*
- 2. They are much better at reducing peak pressures than PU foam cushions and distribute pressure evenly over a much larger area of the cushion.*
- 3. They provide a well-ventilated and comfortable cushion.*
- 4. They can be laundered in a washing machine, are non-flammable and can be easily recycled.*

1 INTRODUCTION

Decubitus ulcers also known as pressure ulcers are a worldwide healthcare concern, affecting tens of thousands of patients and individuals. Susceptibility to decubitus ulcers comes from a combination of external factors (e.g. pressure, friction, shear force, heat and moisture), and internal factors (e.g. fever, malnutrition, anaemia, and endothelial dysfunction)[1].

This has become a significant burden to the NHS and the economy in general. It was previously estimated that the annual expenditure for treating decubitus ulcers was as much as between £1.8 and £2.6 billion [2].

As the population ages, this cost is likely to increase in the future. A final and poignant aspect is that globally decubitus ulcers have resulted in over 28,000 deaths in 2013, increasing from 14,000 deaths in 1990 [3], given the continued ageing of the population, this figure can only increase.

The areas discussed in this paper are; pressure ulcers, the causes and solutions, focusing on the recent research and innovation programme initiated at the University of Bolton in order to improve further the performance and efficacy of these three-dimensional pressure relieving cushions.

These new developments have been engineered in order to assist in the prevention and treatment of pressure ulcers as suffered by immobile or wheelchair bound individuals.

2 MATERIALS AND EXPERIMENTAL METHODS

2.1 Pressure Ulcers

Pressure ulcers or pressure sores are areas of damage to the skin and underlying tissues that are caused by impaired blood supply and tissue malnutrition as a result of prolonged pressure, friction or shear, moisture and heat [4].

Significant weight bearing areas were identified by Meschan [5], Peterson and Adkin [6] as the Ischial Tuberosities ('IT'), the Sacral Coccygeal area, the greater and lesser Trochanters and the Intertrochanteric Crests, which receive excessive pressures when a person is in a sitting position. The 'IT' are located approximately 10cm apart in females and slightly closer in males [5]. The weight distribution is mainly over the tips of the 'IT' when sitting in a normal erect position with no pelvic tilt. Typically, the 'IT' lie 5 to 13 cm from the back of a typical wheelchair back panel [6]. These anatomical pointers take on a significant importance when used in the development of an effective contoured pressure relieving wheelchair cushion.

2.2 Three-dimensional Knitted Spacer Fabrics

Three-dimensional (3D) knitted spacer fabric is a knitted fabric consisting of two separate knitted surfaces which are joined together back to back and kept apart by an inner layer of monofilament spacer yarns. There are two types of knitted spacer fabrics, weft knitted spacer fabrics and warp knitted spacer fabrics. This research utilises the second type, warp knitted spacer fabrics, which are knitted on a double-needle bar warp knitting machine, normally Karl Mayer RD4N and RD6N machines [7]. Typical warp knitted spacer fabrics exhibit 'Isotropic' characteristics in their tenacity, breaking extension and initial modulus properties. Additional properties such as water vapour transmission and heat evaporation are intrinsic to a pressure relieving device [8].

Thermophysiological properties such as thermal absorptivity, thermal resistance and air permeability in warp knitted spacer fabrics have been studied by X.Ye et al [9], with the following conclusions: In comparison with PU foam, warp knitted spacer fabrics are able to transfer heat

away from the human body more easily than PU foam and this was due to a much higher heat conductivity and a lower heat resistance than the foam. Warp knitted spacer fabrics also exhibit better air permeability, as compared to PU foam of similar thicknesses [9], see Tables 1 and 2.

Table 1. Thermal properties of polyurethane foam and warp knitted spacer fabrics [9]

| Sample | Thickness h (mm) | Thermal conductivity λ (W/m K) $\times 10^{-3}$ | Thermal absorptivity (heat absorption capacity) b (W s ^{1/2} /m ² K) | Heat resistance R (m ² K/W) $\times 10^{-3}$ |
|--------|-----------------------|--|---|--|
| C1 | 16.16 | 90.30 | 41.30 | 221.30 |
| A2 | 17.75 | 108.00 | 90.30 | 141.50 |

* Sample 'A2' is a warp knitted spacer fabrics and sample 'C1' is a PU foam fabric.

Table 2. Air permeability of samples [9]

| Sample no. | A1 | A2 | A3 | B1 | B2 | C1 | C2 |
|--|-------|-------|-------|---------|---------|-------|-------|
| Air permeability (l/s/m ²) | 4,204 | 4,197 | 4,188 | 3,307.2 | 3,306.8 | 923.8 | 54.8 |
| Thickness (mm) | 17.93 | 17.75 | 1754 | 28.02 | 43.70 | 16.16 | 14.05 |

* Samples 'A's and 'B's are warp knitted spacer fabrics and samples 'C's are PU foam fabrics.

2.3 Contouring/shaping

A pressure relieving cushion that does not reflect the human body shape at its interface will inevitably result in maximum pressures at high risk areas.

Research conducted by Carlson et al [10] shows that, deeper cushioning by itself will continue to exhibit high pressure points at the same high risk areas.

The most obvious feature affecting this redistribution of pressure is a shaped recess under the pelvis area, taking in the 'IT' area. This feature helps to reduce pressure on the less compliant bony areas and transfer those loads to areas such as the posterior thighs, which have greater compliance and tolerance to pressure [10]. An added advantage of contouring the surface interface of a wheelchair cushion is to increase the accuracy and repeatability of the individual's position on the seat.

2.4 New Methodology

During human trials, the effects of bodily movements can include changes in pressure and distribution. This would vary from human test subject to test subject, giving extremely variable results. The removal of human participants at this stage would help to reduce the variability of testing previously seen with human subjects. For this stage of the research, it was therefore decided to develop an 'ideal' facsimile of the 'human buttocks' for this new methodology. Work had already been carried out by other Researchers [11 - 14] in creating a more standardised facsimile of the 'human buttocks' in a seated position.

'Rigid Cushion Loading Indenters' (RCLI) have been developed and used in a number of newly drafted standardised test methods and research studies, for assessing the characteristics of seat cushions [15 - 18]. The RCLI described in the International Organisation for Standardisation (ISO) 16840-2 (ISO 2007) [18, 19] is a simple representation of the human buttocks, which can be produced in both solid and hollow forms. The ability of this specific shape to generate loading simulations, similar to that seen in human volunteers, has been demonstrated by Staarink [11].

2.5 Rigid Cushion Loading Indenter (RCLI):

An RCLI was fabricated in wood to create a solid template for this research work. This, in combination with a Denison® Universal Tester and a Pressure Mapping System, was the ensemble used to test and analyse pressure distribution in pressure relieving cushions and enable the development of novel prototype designs for pressure relieving wheelchair cushions. The Boditrak Pressure Mapping System from Vistamedical, Canada was used for this research and consisted of a sensor mat with 16x16 sensors (sensor count =256), sensing area of 645mm² and a standard pressure range of 0 to 200 mmHg [20].

The RCLI is attached to the central column of the universal tester, with the test cushion placed in a set position beneath the RCLI. The pressure mat is positioned on top of the cushion and linked to the FSA software on a computer. The RCLI is lowered onto the cushion to a set load, peak and average pressure distributions are measured and recorded, creating pressure mapping profiles covering the whole covered area of the cushion.

Pressure mapping measurements were taken under a series of different loading pressures, held in position and released for set time periods.

A cycling programme was developed to test the validity of the test method and generate a suitable amount of data in order to characterise each prototype.

Each cycle applied set loads of 0.500kN and 0.750kN, held for a fixed time period of 15 minutes. The loads were released and the cushions were allowed to rest for 30 minutes. The cycle was repeated continuously by using a software programme linked to the Denison Universal Tester, which allows the cycles to be repeated as many times as needed, to test repeatability of the test results. The pressure mapping software recorded pressure results throughout all the cycles, capturing data both numerically and graphically. Data was captured by using the 'Recording' mode of the FSA software which records results continuously. The results were analysed at the initial loading stage of the cushions and after being applied for 15 minutes. The cycles were compared for repeatability of results and to examine variability throughout the testing periods. The work is continuing to refine and further develop this methodology.

The pressure mapping test apparatus consisted of the following equipment:

- Rigid Cushion Loading Indenter (RCLI) [19]
- Denison Universal Tester
- Boditrak Pressure Mapping System [20]
- Laptop

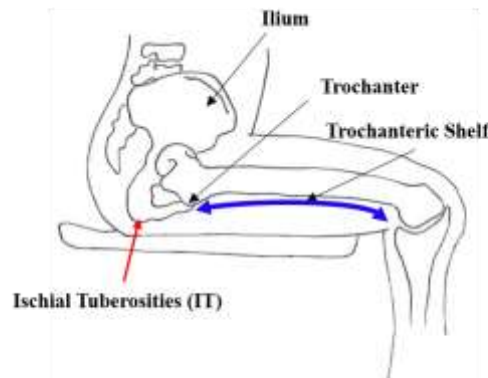
2.6 New Developments

These new research developments started with reducing the high pressure points in the Ischial Tuberosities ('IT') area, by using the shape of the human buttocks as a starting point.

A shaped recess was created at the back of the cushion, to enable a reduction of pressure at the back, where the 'IT' are positioned. The recess in the 'IT' area, was created by using a combination of multiple layers of knitted spacer fabric, these were cut and castellated to eliminate the high pressure points.

Two prototypes models ASD4 and ASD5 were developed by using different combinations of 20mm and 6mm thick warp knitted spacer fabric structures. Construction details of prototype cushions ASD4 and ASD5 can be found in Table 3.

Initial testing of these first prototypes, by using the new methodology revealed a reduction in peak pressures in the ‘IT’ area, transferring more pressure down the thighs by using the less vulnerable Trochanteric Shelf, as shown in Figure 1.



Main areas of support in the seated position are the Ischial Tuberosities and the Trochanteric shelf.

Figure 1. Anatomical areas of support in the sitting position

Table 3. Specifications of ASD4, ASD5 and PU Foam Cushions

| Prototypes | Layers | Core specification | Thickness | Shape/contouring |
|--|----------|--|--|--|
| ASD4 – Full contoured recess | 5 layers | A – Quality A1301 B – Quality M8960 C - Quality M8960 D - Quality M8960 E- Quality D010002 | 6.0mm 20.0mm 20.0mm 20.0mm 6.0mm | Recess created at layers B & C, cut and castellation, and cut only respectively. |
| | | TOTAL = | 72.0mm | |
| ASD5 – Partial contoured recess | 5 layers | A – Quality A1301 B – Quality M8960 C - Quality M8960 D - Quality M8960 E- Quality D010002 | 6.0mm 20.0mm 20.0mm 20.0mm 6.0mm | Recess created at layers B only, cut and castellated. |
| | | TOTAL = | 72.0mm | |
| PU Foam | 1 layer | PU Foam | 80.0mm | Flat PU foam |

3 RESULTS

Testing by using the new methodology was carried out on the Airospring® model AS200, ASD4, ASD5 and PU Foam. These results can be seen in Tables 4 and 5. Pressure mapping results have been recorded on initial loading of the cushion and after 15mins of loading of the cushion. The compressive loads applied were 0.500kN (approximately 50kg) and 0.750kN (approximately 75kg). As the pressure results were continually changing, the software calculates the mean, standard deviation (σ) and coefficient of variation (CV%) for each set of data.

With an increase in the load and time, more spreading occurred to the less vulnerable areas. By using the video capture mode of the pressure mapping test, fluctuations of pressure could be seen as the 3D knitted spacer fabric re-distributes the pressure around the cushion. The RCLI became immersed in the cushion, as the cushion moulds and settles around the shape of the RCLI, while continually re-distributing the pressure, as the spacer structure successfully accommodates the pressure applied to it.

The novel structure created in the IT area, re-distributes the peak pressure that normally occurs in this area and spreads it along the trochanteric shelf. With an increase in time, the pressure spreads to a greater area. This can be seen in ASD4 and in ASD5 at a load of 0.500kN, where the spread of the load has increased from time of initial loading to 15mins later. The pressure is distributed mainly in the thigh area, which is a less vulnerable part of the human anatomy.

The structure of the ASD4 prototype gives a more ‘gentle’ spread of pressure, than a simple hole in the ‘IT’ area, which is harsher and gives additional pressure points. This construction also seems to encourage moulding in the recess area when additional weight is added, taking advantage of the 3D construction of the fabric and making use of the resilience of the spacer fabric.

Tables 4 and 5 summarise the pressure mapping data collected for the Airospring® AS200 cushion, ASD4 and ASD5 new prototype cushions and PU foam, recording the average overall pressure results for each cushion.

The data from these prototypes clearly shows the significant advantages of 3D warp knitted spacer fabrics in the construction of pressure relieving wheel chair cushions. The substantial reduction in average overall pressure during initial sitting and over time is illustrated in Tables 4 and 5. The maximum peak pressures reached in ASD4 and ASD5 are also much lower than PU foam which is seen to reach the maximum pressure of 200mmHg, this is illustrated in Figure 5. The pressure map profiles of ASD4 and ASD5 in Figures 3 and 4 illustrate the re-distribution of peak pressure points, which would have occurred in the IT area.

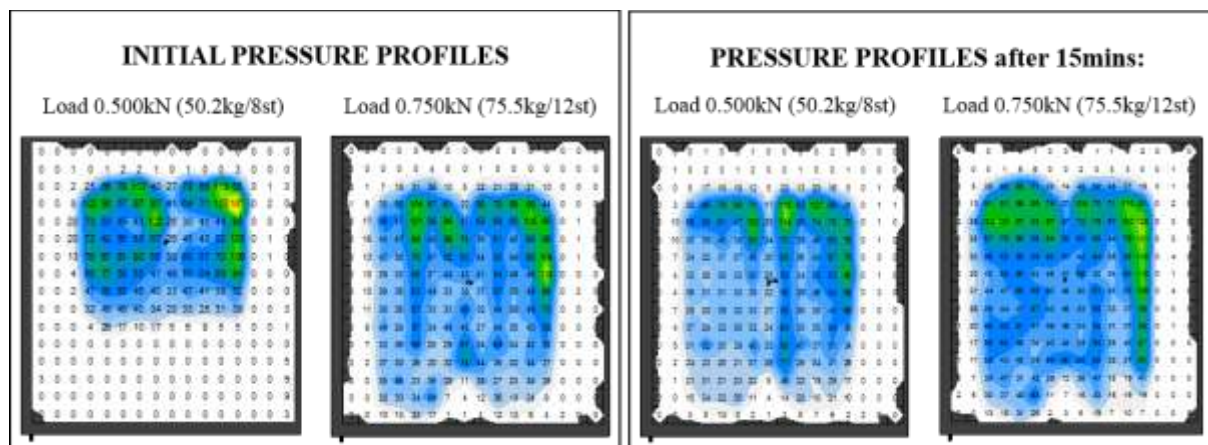
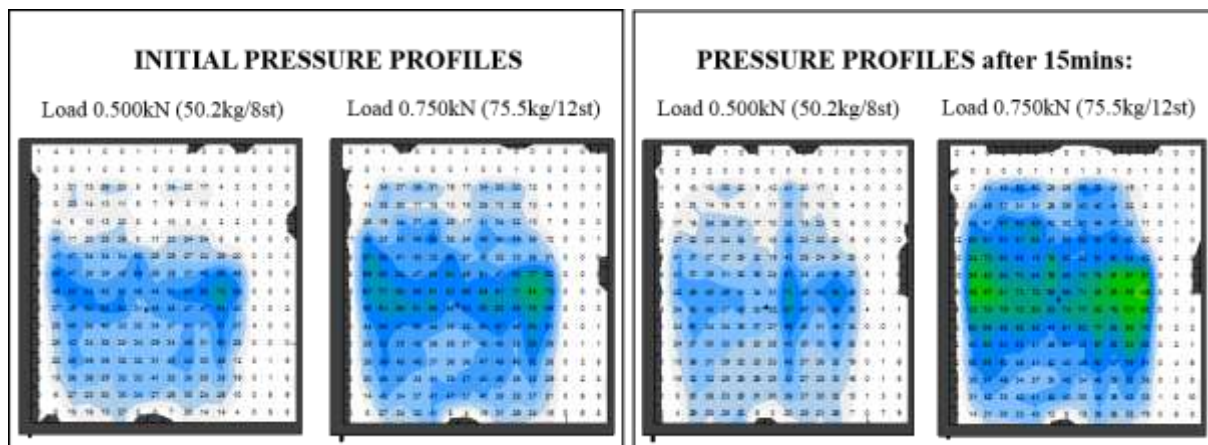
The additional ability to disperse heat and moisture as well as pressure, makes warp knitted spacer fabrics an excellent choice of materials to use in the construction of pressure relieving wheelchair cushions.

Table 4. Comparative summary of pressure mapping results at initial loading

| | Initial loading of 0.500kN at time ‘0’ | | | |
|------------------------------|---|-----------------------------|--------------------------------|-----------------------------|
| Cushions | AS200 FLAT | ASD4 FULL RECESS | ASD5 PARTIAL RECESS | PU FOAM FLAT |
| Maximum Value (mmHg) | 93.8 | 80.3 | 81.7 | 200.0+ |
| Mean (mmHg) | 35.1 | 29.1 | 33.7 | 54.4 |
| Standard deviation (mmHg) | 17.5 | 18.8 | 20.5 | 34.7 |
| Coefficient of variation (%) | 49.7 | 64.5 | 59.6 | 61.8 |
| | Initial loading of 0.750kN at time ‘0’ | | | |
| Cushions | AS200 FLAT | ASD4 FULL RECESS | ASD5 PARTIAL RECESS | PU FOAM FLAT |
| Maximum Value (mmHg) | 133.9 | 90.7 | 87.4 | 200.0+ |
| Mean (mmHg) | 42.7 | 45.4 | 39.7 | 59.2 |
| Standard deviation (mmHg) | 24.6 | 18.3 | 16.9 | 41.3 |
| Coefficient of variation (%) | 57.5 | 40.4 | 42.0 | 69.3 |

Table 5. Comparative summary of pressure mapping results after 15mins loading

| | Loading of 0.500kN after 15mins | | | |
|------------------------------|---------------------------------|---------------------|------------------------|-----------------|
| Cushions | AS200 FLAT | ASD4 FULL RECESS | ASD5 PARTIAL RECESS | PU FOAM FLAT |
| Maximum Value (mmHg) | 174.7 | 62.2 | 105.3 | 200.0+ |
| Mean (mmHg) | 45.1 | 21.1 | 40.6 | 50.6 |
| Standard deviation(mmHg) | 33.1 | 11.8 | 20.2 | 42.6 |
| Coefficient of variation (%) | 73.5 | 43.4 | 49.5 | 83.9 |
| | Loading of 0.750kN after 15mins | | | |
| Cushions | AS200 FLAT | ASD4 FULL RECESS | ASD5 PARTIAL RECESS | PU FOAM FLAT |
| Maximum Value (mmHg) | 121.1 | 105.1 | 131.2 | 200.0+ |
| Mean (mmHg) | 51.6 | 51.3 | 53.9 | 65.0 |
| Standard deviation(mmHg) | 24.9 | 20.0 | 25.5 | 46.1 |
| Coefficient of variation (%) | 48.2 | 38.8 | 47.4 | 70.6 |

**Figure 2.** Pressure mapping profiles for Airospring® AS200 wheelchair cushion by using new methodology**Figure 3.** Pressure mapping profile images of ASD4 prototype wheelchair cushion by using new methodology

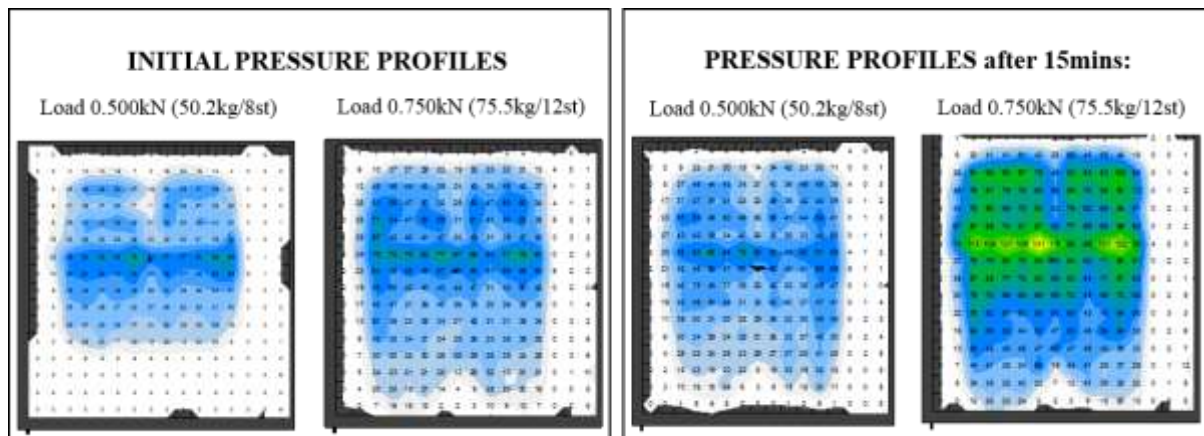


Figure 4. Pressure mapping profile images of ASD5 prototype wheelchair cushion by using new methodology

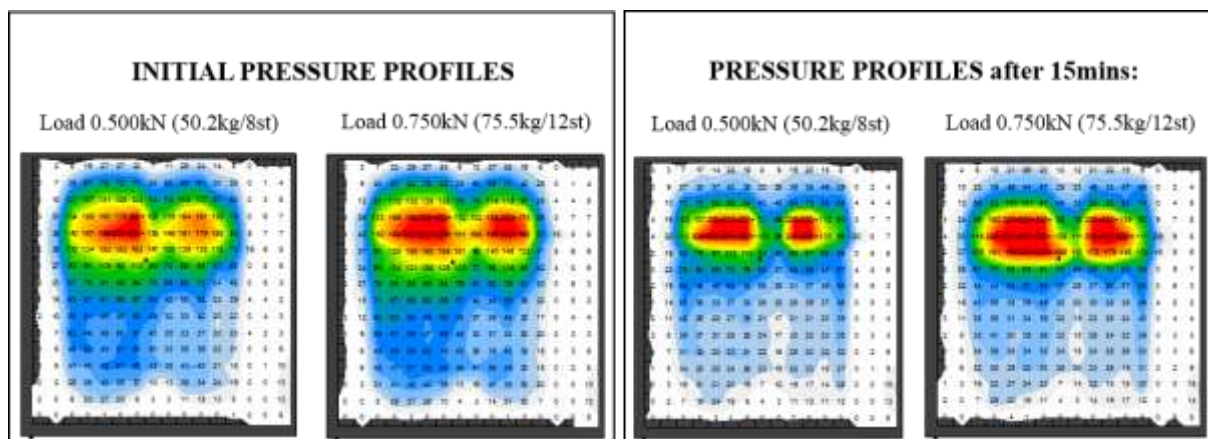


Figure 5. Pressure mapping profile images of PU Foam wheelchair cushion by using new methodology.

4 CONCLUSIONS

Some key conclusions drawn from this research work are as follows:

- Thicker warp knitted spacer structures, or multi layers of different thicknesses may be used to develop effective contoured structures.
- Warp knitted spacer fabrics retain their thickness over long periods of both static and dynamic loading. This is mainly due to the superior resilience of the material.
- Shaped/contoured cushions encourage greater reduction of pressure in the IT area than flat cushions.
- Multi-layered warp knitted spacer fabrics by using a shaped/contoured recess, encourages further reduction of pressure in the vulnerable Ischial Tuberosities area.

- Multi-layered contoured warp knitted spacer structures are better at reducing peak pressure in the vulnerable areas than PU foam. Furthermore, they distribute the pressure more evenly over much larger areas of the cushion than PU foam.
- Warp knitted spacer fabrics inherently possess superior thermophysiological comfort properties than PU foam, due to their higher thermal conductivity and lower thermal resistance than the PU foam products.
- As established in other studies [7, 8], warp knitted spacer fabrics are much more breathable substrates for pressure relieving wheelchair cushions. They are also extremely efficient in the dissipation of both water vapour, as well as the moisture away from the body.
- Airospring® is the brand name of fully patented cushions AS100, AS200 and all other shaped/contoured cushions developed and fully characterised in this research work. They are machine washable and can be tumble dried. They are non-flammable and recyclable, since only one fibre type, polyester, is used throughout the cushions.

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